

The Future of Quark Matter at RHIC

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The matter discovered at RHIC has shown a number of very surprising properties. It is extremely dense and has an initial energy density well above that expected for the phase transition from ordinary hadronic matter into quark gluon plasma. [1–4] The dense matter is very opaque to colored particles, such as quarks or gluons, traversing it. This gives rise to the striking jet quenching observed at RHIC. [5,6]. Measurements of the elliptic flow of different hadrons indicate that the plasma at RHIC is a liquid with extremely low viscosity. [1–4] Furthermore, there is substantial evidence that hadron formation results from coalescence of constituent quarks from the collectively flowing medium. [7]

It is natural to ask how this hot, dense partonic liquid transports particles, energy, momentum and charge. This means we should determine its diffusion constant, thermal conductivity, viscosity and (color)electric conductivity. Extracting such quantities quantitatively requires significant advances in both fundamental theory and phenomenology. Of course, these must be accompanied by extensive, high precision measurements. In this paper, we will discuss how increased luminosity at RHIC, along with upgraded detector capabilities, will probe how this new kind of plasma works.

Upgrading the luminosity at RHIC is compelled by two kinds of questions. There are basic questions which for which we don't yet have sufficient data. And there are entirely new questions, which arose from the initial discoveries at RHIC. Such new questions include:

- What is the mechanism for rapid thermalization?
- How low is the viscosity of the liquid?
- How does the plasma respond to deposited energy?
- What is the color screening length?
- Is the initial state a color glass condensate?

Early questions not yet answered by data are:

- What is the nature of phase transition? Where is the critical point?
- What is the equation of state of hot QCD matter?
- Do heavy quark bound states melt?
- Can dilepton observables provide evidence for chiral symmetry restoration?

Lattice QCD indicates that the phase transition should occur above an energy density of 0.6 GeV/fm^3 and temperature of 150 MeV. [8] The ratio of energy density to temperature, ϵ/T^4 increases rapidly, and then levels off within the range $150 \leq T \leq 300$ MeV. The RHIC collider thus can probe exactly the region of interest. The addition of

electron cooling of the heavy ion beams will counteract beam blow-up due to Coulomb interactions in the dense beams of highly charged particles. Cooling will increase the luminosity for heavy ion collisions by an order of magnitude. This will allow, among other things, a scan of colliding beam energies to search for the critical point with good statistical precision. In addition, completion of the new Electron Beam Ion Source (EBIS) will offer the first ever collisions of uranium beams. U+U collisions with high luminosity will allow probing systems with 30% higher energy density, by selecting the collisions in which the non-spherical uranium nuclei are aligned end-on.

Both the STAR and PHENIX experiments have undertaken a number of detector upgrade projects. These will maximize the benefit from higher collider luminosity, but will also greatly increase the physics reach of the experiments even before the luminosity upgrade is complete. STAR is currently implementing a large barrel time-of-flight upgrade to increase particle identification capabilities, a forward meson spectrometer to allow measurement of neutral mesons at forward rapidity, and preparing a data acquisition and TPC readout upgrade to enhance STAR's data acquisition rate capability. In the near future, STAR plans to construct a tracking upgrade consisting of a heavy flavor tracker (HFT) pixel detector, barrel and forward silicon trackers, and a forward triple-GEM EEMC tracker. PHENIX is constructing a Hadron Blind Detector for background rejection under low mass dileptons, a Muon Piston Calorimeter at forward rapidity, and a barrel silicon vertex tracker to identify open heavy flavor decays. In the future, work will begin on a forward vertex tracker and compact calorimeter extending the rapidity reach of PHENIX for photons and neutral mesons to the region $1 \leq y \leq 3$. The combination of calorimetry and tracking will give PHENIX a large acceptance for γ -jet coincidences.

Better determination of the viscosity and equation of state of the plasma at RHIC will require improved measurements of radial, directed, and elliptic flow for different mass hadrons. The particle mass dependence reflects the equation of state. The flows of multi-strange hadrons will help to differentiate late stage dissipation from early viscosity. Heavy meson elliptic flow and diffusion through the plasma will pin down the thermalization time and viscosity, and show how these vary with beam energy. The detector upgrades described above will greatly improve the particle identification capabilities of both STAR and PHENIX to make this possible. Of course, for these measurements to produce precision science requires that RHIC scan in energy and system size (which will become possible with the higher luminosity of RHIC II), as well as careful comparison to viscous 3-dimensional hydrodynamics calculations. Significant progress in theory and phenomenology will be needed to make this possible. Furthermore, fundamental theory breakthroughs are needed to quantitatively understand the initial state in heavy ion collisions, pin down the thermalization mechanism, identify experimental observables of instabilities, and calculate pre-equilibrium dynamics of the matter.

In traditional plasma physics, it is common to use externally generated probes and measure their transmission through the plasma. At RHIC, determining the response of our plasma to deposited energy requires something equivalent to the plasma physicists' "external" probes. Heavy ion collisions provide just such probes, autogenerated in the collision itself, arising in the initial hard scatterings among partons in the nuclei. The production rate and distribution are calculable with perturbative QCD, and are experimentally well calibrated in p+p collisions. These hard probes interact with the medium as they traverse it; jets and heavy quarks are of particular interest. Experimentally, the goal is to measure the fate of the probe, along with associated

plasma-generated particles.

Transport in plasmas is driven primarily by collisions. Diffusion is a measure of the transport of particles by the plasma. The transport of energy by those particles is given by the thermal conductivity. Viscosity is a measure of the transport of momentum by particles, while electrical conductivity measures how effectively the particle collisions transport charge. Precise determination of transport properties will require substantial progress in theory, in particular development of techniques to handle transport in a medium where the coupling between particles is not weak. A number of ideas were discussed at this conference, ranging from next-to-leading order perturbative calculations of energy loss in an expanding medium, resummation techniques to allow the application of perturbation theory to strongly coupled regimes, scattering of particles from color fields, possibly coherent, and application of AdS/CFT correspondence to allow use of gravitational calculations in the infinitely strongly coupled limit. It is clear that we are only beginning to learn how to make the problem tractable.

Existing data have established the usefulness of heavy quarks and jets as good candidate plasma probes, but current energy reach and precision are far short of what is required. As these are rare processes with triggerable signatures, the RHIC II luminosity will provide an enormous improvement. There are three basic measurements required. One is spectroscopy of heavy quarkonia, to determine the screening length in the plasma and fate of heavy bound states. This will require measurement of J/ψ , ψ' and Υ states. Another is to measure the correlations of hard particle pairs to study the mechanism by which fast quarks or gluons lose energy to the medium. High statistics measurements of hadron fragments with $p_T > 5$ GeV/c arising from 10-30 GeV jets are needed for substantial progress. The medium response to the lost energy is probed by two and three-particle correlations, with a hard trigger particle and medium-generated associated particles with $1 \leq p_T \leq 4$ GeV/c.

It is natural to wonder about the role of RHIC II, as hard probes are major goals of the heavy ion program at the LHC. At RHIC II, the high luminosity, long running time, and flexibility of the accelerator complex provide an extremely compelling – and competitive – physics program with hard probes. The higher cross section at LHC energy is more than compensated by the larger integrated luminosity at RHIC II.

J/ψ suppression was predicted 20 years ago as a signature of deconfined matter [9]. Since then, charmonium production has been extensively studied. At the CERN SPS, NA50 measured “normal” J/ψ suppression in cold nuclear matter, *i.e.* in p+A collisions, and “anomalous” suppression in A+A collisions. [10] The observed decrease of the J/ψ yield in central A+A collisions has been interpreted as indicating deconfinement. However, this interpretation is complicated by the fact that PHENIX observes a similar level of suppression despite considerably higher energy density at RHIC. [11] It is conceivable that the suppression signals sequential melting of different charm quark bound states, along with feeding by decays of heavier states. Indeed, such a result would be expected for a strongly coupled plasma in which the c and \bar{c} potential is not fully screened. However, it may also be that the primordial J/ψ is more suppressed at RHIC than at the SPS and the additional suppression is canceled by final state coalescence of charm and anti-charm quarks. Sorting this out unambiguously will require measuring multiple bound states for several beam energies and systems. These measurements, with higher precision and significantly larger p_T reach, should allow determination of the color screening length in the plasma by comparing the fate of bound states with different radii. Significant theory work is needed as well, if we are

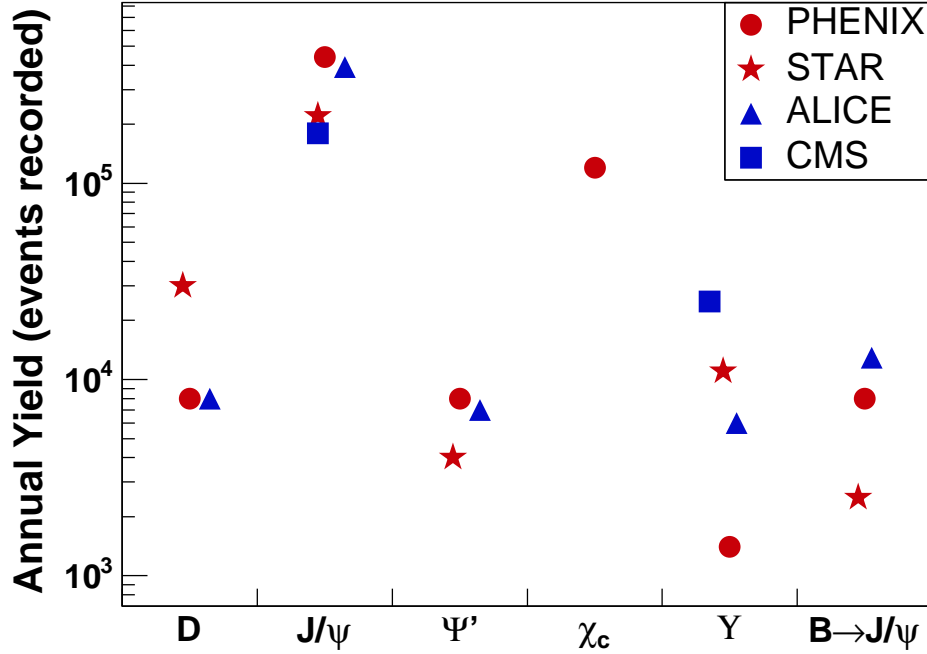


Figure 1. Expected annual yield for various mesons containing heavy quarks detected in minimum bias collisions of the heaviest ions. The PHENIX and STAR estimates (red symbols) are for Au+Au at RHIC II luminosity, in a run of 12 weeks duration. ALICE and CMS estimates (blue symbols) are for Pb+Pb collisions at LHC with design luminosity and 1 month of data taking.

to fully understand the role of apparently canceling processes. Calculations need to be done that include a well-defined initial state (for example, color glass condensate), color screening, and bound state regeneration in an expanding medium. The effect of strong coupling in the medium upon heavy quark bound states needs quantitative exploration; this has begun using lattice QCD, but dynamics are an important component.

Figure 1 shows the expected number of events with detected heavy flavor in one run for PHENIX and STAR at RHIC II and for the ALICE and CMS experiments at the LHC. It should be noted that the RHIC II run length used is 12 weeks, which corresponds to approximately one half of a year's worth of beam time. Good triggering capability is assumed for all four experiments. The rates are for minimum bias Au+Au and Pb+Pb collisions at RHIC II and LHC, respectively. It is clear that the number of heavy particles recorded will be quite comparable at the two facilities. This seems surprising, as the production cross sections are higher by a factor of 10-50 at the LHC, depending on the species. The similarity arises because the RHIC II luminosity will be a factor of 14 higher, and the running 3-4 times longer.

It should be noted that charmonium states will be of limited utility as probes of color screening at the LHC. Because of the high initial temperature, there will be substantial thermal production of charm quarks, and the majority of the charm anti-charm bound states should be formed by final state coalescence. Consequently,

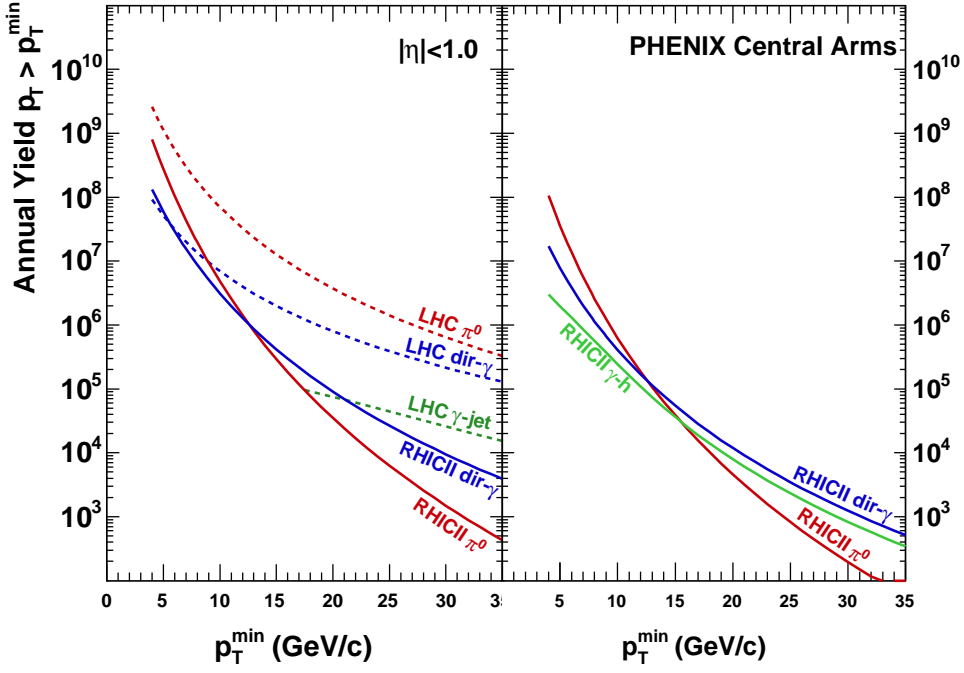


Figure 2. Annual recorded number of events of neutral pions, direct photons, and photon-jet coincidences at RHIC II and LHC, based upon NLO pQCD from W. Vogelsang and scaled to minimum bias Au+Au or Pb+Pb collisions (see text for details). The left panel shows yields into two units of rapidity centered at $y=0$ and full azimuth, while the right panel shows yields into the PHENIX central arms.

charmonia at LHC will not provide detailed information about the early state of the medium at its hottest and densest. This role will be open to B quark states only. The planned χ_C measurement by PHENIX is very challenging due to large backgrounds. It is expected that the RHIC II sample will allow statistical separation of the signal from the background. At the LHC, the background will be larger still, most likely proving prohibitive for this measurement.

Turning now to jet probes of energy loss and transport in the hot and dense medium, we compare the physics reach at RHIC II and LHC. Correlations of two or more high momentum particles arising from fragmentation of back-to-back jets probe the mechanism of energy loss. Such information can be gleaned from 10-30 GeV jets. Because of the lower temperature and smaller soft, or thermal, hadron backgrounds, this physics can be probed with 10 GeV jets at RHIC II. The backgrounds will be larger and have a harder spectrum at the LHC, requiring jet energies of ≈ 30 GeV in order to achieve signal to background ratios comparable to those at RHIC. It should be noted, however, that the collective boost imparted by the jet to co-moving plasma particles is relatively modest. Consequently, it may be that the plasma response information is most prominent in relatively soft jets.

The correlation of one hard particle (> 5 GeV/c p_T) with one or more softer particles ($p_T = 1-4$ GeV/c) from the opposing jet probes the response of the medium

to the energy deposited by a jet traversing it. The “golden channel” for jet probes of the hot, dense medium is direct photon-jet correlations. *direct* γ -hadron pairs arise from QCD Compton scattering; the direct photon tags the jet energy (i.e. the energy of the recoiling quark). By measuring the hadrons from the jet, it should be possible to quantify the lost energy and its fate in the medium.

We estimate the expected annual rates using NLO perturbative QCD calculations from W. Vogelsang, [12] which have been benchmarked by comparison to p+p collisions at RHIC. To predict rates in minimum bias heavy ion collisions at RHIC II and the LHC, the pQCD cross-sections of π^0 and direct photons are integrated above a given p_T threshold, scaled up by A^2 , and multiplied by the expected integrated luminosity. The resulting annual yields are corrected for the observed hadron suppression and direct photon non-suppression in Au+Au collisions at RHIC, and known or expected experiment up time. In lieu of a measured suppression at the LHC we have used the RHIC value of 0.2 also for the LHC calculations. The plotted annual yields show the total number of recorded events with $p_T > p_T^{min}$. Results for single direct γ and π^0 can be seen in Figure 2 as solid lines for RHIC II and dashed lines for LHC. The left hand side shows the annual yield into rapidity $-1 < y < 1$, while the right hand side provides the yield into the PHENIX central arms for comparison. The larger rapidity range reflects the acceptance of STAR and ALICE, however PHENIX will have comparable acceptance once the upgrades are complete.

Two striking results are immediately apparent. The first is that with the γ/π^0 ratio observed at RHIC, direct photons dominate over decay photons above ≈ 12 GeV/c p_T , greatly simplifying γ -jet measurements. The second is that the p_T reach at RHIC II is quite large. Using 1000 counts as a useful minimum, we see that direct photons can be measured to $p_T > 30$ GeV/c at RHIC II.

Yields of events with hadrons of $p_T \geq 4$ GeV/c detected in coincidence with direct photons are also shown in Figure 2. The coincidence probability of single hadrons opposing the direct photon or π^0 trigger in azimuth was estimated with the PYTHIA event generator to be essentially 1.0 for the left panel. The PHENIX event yields are based upon measured conditional yields of away-side hadrons, with PYTHIA used to estimate coincidence rates for higher p_T trigger particles. The figure shows that RHIC II will measure direct photon-hadron coincidences for 35 GeV/c photons. Even the PHENIX central arms alone will access *direct* γ - h for 30 GeV/c photons, though upgrades underway will increase the PHENIX acceptance nearer to that in the left panel.

The LHC γ -jet curve shows expected yields for fully reconstructed away side jets. There will be a good sized sample of such events after one year of running. However, it should be noted that at LHC γ/π^0 remains significantly below 1.0, even at $p_T = 35$ GeV/c, unless the π^0 suppression at LHC were to be much larger than that observed at RHIC. This would be surprising since $R_{AA} \approx 0.2$, observed at RHIC, is consistent with emission only from a thin shell around the surface of the medium. Consequently a significantly larger number of events will be required at the LHC, in order to enable statistical subtraction of decay photon-jet correlations. At RHIC, full jet reconstruction is not available for the relatively low energy jets measured thus far, but reconstruction studies are currently underway.

In order to estimate the yield of events at RHIC II with more than a single hadron correlated with trigger jets and direct photons, we have performed PYTHIA simulations. Figure 3 shows annual yields of events with two hadrons on the away

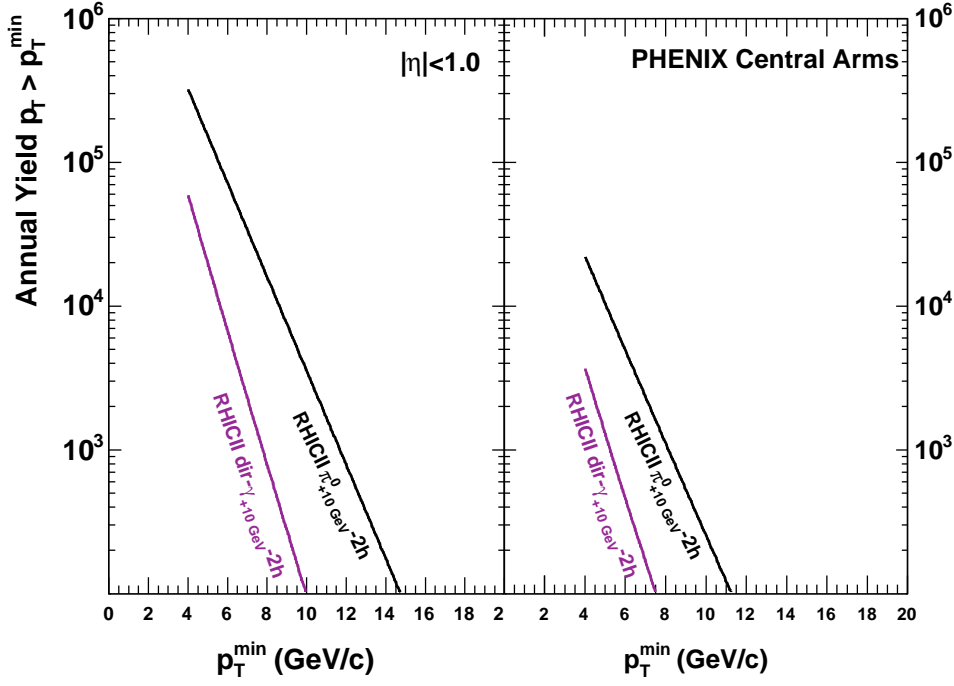


Figure 3. Annual yield of events with two hadrons on the opposing side of a >10 GeV/c direct photon and 10 GeV/c π^0 . The event count is plotted as a function of hadron p_T^{\min} .

side of a ≥ 10 GeV/c direct photon and ≥ 10 GeV/c π^0 . The number of events with two detected hadrons of $p_T \geq p_T^{\min}$ is plotted as a function of hadron p_T^{\min} . For such low energy jets, two hadrons above 4 GeV/c p_T already carry most of the jet energy. The plot shows that a significant event sample will be collected with nearly fully reconstructed away-side jets at RHIC. For higher energy direct photons, the probability of finding two energetic hadrons should increase. Consequently, a significant number of direct photon-two hadron correlations should be expected also for the higher photon energies. The direct photon-2h yields fall more rapidly with hadron p_T than π^0 -2h, as the π^0 carries only a fraction of the jet energy. Photons arise from lower energy jets than a π^0 at the same p_T , and therefore are less likely to have two associated energetic hadrons.

In order to achieve these goals, an upgrade strategy for the RHIC experiments and collider has been defined. Both STAR and PHENIX are constructing short-term upgrades, which will begin taking data in the time frame of 2007-2009. Concurrent with these are steps to increase the RHIC luminosity through improvements in vacuum quality and increasing the number of bunches in the machine. The new EBIS source should be commissioned in 2009. Larger scale upgrades for both experiments will begin construction in 2007 and 2008, in order to be complete before 2011. The detector upgrades will be available for data-taking prior to the start of the heavy ion program at the LHC. Brookhaven envisions beginning construction work on the RHIC II luminosity upgrade around 2009 or 2010, with commissioning three years later.

The enabling technology for RHIC II is electron cooling of the ion beams to mitigate beam blow-up from Coulomb scattering. It is interesting to note that the electron cooling that increases RHIC's luminosity ten-fold also positions RHIC for use as an electron-ion collider. This would entail adding a 20 GeV electron accelerator, along with a new detector, to the complex.

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References

- [1] K. Adcox, et al. (PHENIX Collaboration), *Nucl. Phys.* **A757** (2005) 184.
- [2] J. Adams, et al. (STAR Collaboration), *Nucl. Phys.* **A757** (2005) 102.
- [3] B.B. Back, et al. (PHOBOS Collaboration), *Nucl. Phys.* **A757** (2005) 28.
- [4] I. Arsene, et al. (BRAHMS Collaboration), *Nucl. Phys.* **A757** (2005) 1.
- [5] K. Adcox, et al. (PHENIX Collaboration), *Phys. Rev. Lett.* **88** (2002) 022301 .
- [6] C. Adler, et al (STAR Collaboration), *Phys. Rev. Lett.* **89** (2002) 202301.
- [7] R.J. Fries, B. Muller, C. Nonaka and S.A. Bass, *Phys. Rev. Lett.* **90** (2003) 202303; R.C. Hwa and C.B. Yang, *Phys. Rev.* C70 (2004) 024905; V. Greco, C.M. Ko and P. Levai, *Phys. Rev. Lett.* **90** (2003) 202302.
- [8] F. Karsch, Lect. Notes Phys. **583** (2002) 209.
- [9] T. Matsui and H. Satz, *Phys. Lett.* **B178** (1986) 416.
- [10] J.C. Abreu, et al. (NA50 Collaboration), *Phys. Lett.* **B477** (2000) 28.
- [11] A. Adare, et al. (PHENIX Collaboration), nucl-ex/0611020 (2006).
- [12] A. Mukerjee, M. Stratmann, and W. Vogelsang, *Phys. Rev.* **D72** (2005) 034011; and W. Vogelsang, private communication.